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This proposal addresses the development of a softcopy display for digital mammography that seeks to couple optimally the visual system to the displayed image without excessive human-machine interaction. It also breaks away from two traditional approaches to workstation display design, namely trying to make the softcopy image look like hardcopy and using observer determined window-level and rove-zoom function.

The display is calibrated by using both the perceptually standard curve for the monitor and an observer derived display based upon the just noticeable difference in contrast over the intensity range of the monitor. The image is equalized to fit the prescribed intensity range. There is also a built in scanning procedure derived from eye-position observation on skilled mammographers.

The calibration procedures are being tested and the scanning procedure is being developed.

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Abstract

This proposal addresses the development of a softcopy display for digital mammography that seeks to couple optimally the visual system to the displayed image without excessive human-machine interaction. It also breaks away from two traditional approaches to workstation display design, namely trying to make the softcopy image look like hardcopy and using observer determined window-level and rove-zoom functions.

The display is calibrated by using both the perceptually standard curve for the monitor and an observer derived display based upon the just noticeable difference in contrast over the intensity range of the monitor. The image is equalized to fit the prescribed intensity range. There is also a built in scanning procedure derived from eye-position observation on skilled mammographers.

The calibration procedures are being tested and the scanning procedure is being developed.

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5. Introduction

5.1. Purpose of the Project

The long term goal of this research is to improve the detection of masses on digital mammograms by using a softcopy display that will optimize the coupling of the human visual system to the display without excessive human-machine interaction. This coupling is called a "perceptually tempered" softcopy display.

5.2. Scope of this Project

This problem will be approached by three related aims.

Aim 1: Develop a method for simulating masses of realistic appearance on real mammographic parenchymal backgrounds that can be used as a test set for the subsequent development of display methods.
Aim 2: Develop a method for equalizing perceived contrast on a mammogram that is related to the contrast sensitivity of the reader.
Aim 3: Develop a computer controlled roving window based upon eye position distribution patterns over mammograms.

5.3. Background

For the foreseeable future, mammograms will be the primary screening tools for breast cancer and they will be read by human beings. Whenever images are read by human beings there is an associated error rate. Although the true diagnostic accuracy for screening examinations is unknown, false negatives (misses) have been estimated to range between 11 and 25 % and false positives have been estimated to range between 10 and 35 %. These figures indicate that there is room for improvement in the readers.

Digital detectors will be a reality in the near future making softcopy readings feasible. Softcopy has many potential advantages but at present is less effective than hardcopy. Simulating film with a softcopy display is inadequate because as compared with film currently available monitors do not have sufficient intensity range , do not have sufficient resolution and are too noisy. Although bright (1000 cd/m^2), high resolution (4000 x 4000 pixel) monitors are feasible, they are too expensive for widespread use. The window-level and zoom-rove functions that are commonly used with cross-section CT and MRI are not sufficient for mammograms. Given the present state of the art, softcopy displays cannot be made that simulate film. Therefore, it is important to develop display mode alternatives to the film-on-lightbox design or cross-section imaging design that can be used with moderate brightness (300 cd/m^2), moderate resolution (2000 x 2000 pixel) monitors.

Johnson et al. [8.1] and Blume et al. [8.2]have suggested that video monitors should be "perceptually standardized" so that equal changes in the pixel gray scale value produce equal changes in the just noticeable difference (JND) of luminance in the image. Although perceptual standardization is a worthwhile way to make monitors adhere to the same standard input-output transfer characteristic, it does not adjust either for local contrast variations in the image or for the level of light adaptation which is partially determined by the ambient lighting. In order to match the display of a particular image to the visual system, the image itself must be modified and the display function must be adjusted for the adapting luminance. In our laboratory, Liu and Nodine [8.3] using a model first proposed by Mokrane [8.4] have developed an algorithm that equalize perceived luminance over the image assuming some starting level of adapting luminance. Contrast is modified in the image on the basis of the theoretical threshold-contrast curves of Heinemann [8.5].

This research extends the work of Liu and Nodine [8.4] to include calibration of the individual observer and to incorporate perceptually derived scanning strategies into the search for masses on mammograms.

6. Progress Report

6.1. Development of Simulated Mass Lesions on Real Mammographic Backgrounds

A set of images was selected from a group of mammograms known to be normal (stable for 3 years). The images were digitized at 100 microns resolution and square sections about 10 x 10 cm in size were removed from each image and placed in a file. A computer program was developed to simulate the appearance of the projection of an object onto the mammogram background. The free parameters in the program include the size of the ovoid object (size and shape), the linear x-ray attenuation coefficient of the object and the surround (contrast) and a geometric unsharpness factor (focal spot size and distance). The simulator is used by randomly selecting a section and a point in the section. The section is then displayed with the mass centered on the selected point.

The simulator provides an inexhaustible supply of very low contrast masses on real mammogram backgrounds for use in testing the system.

6. 2. Development of display software and a calibration procedure to compensate for several phenomena that may hinder the detection of abnormalities in mammograms

6.2.1 Photometric calibration of the display

The input-output transfer characteristic of display monitors limit the number of distinguishable gray levels, even under the most favorable of ambient room lighting conditions. The assignment of available gray levels for displayed images is optimized by photometric calibration followed by perceptual adjustment.

A photometer is aimed at the center of the monitor and the intensity of a square larger than the active area of the photometer is stepwise increased. A plot of luminance against the digital driving intensity is made. The brightness and contrast controls of the monitor are adjusted to provide visualization of the maximum number of gray levels following the method proposed by Blume et al. [8.2].

6.2.2 Perceptual calibration of the display

Psychophysical measures on observers viewing subtle targets show that at any light adaptation level of the human eye, performance degrades when the target surround is sufficiently different than the light levels dictating the adaptation level of the eye. A psychometrically derived correction to the display lookup tables is used to boost the displayed contrast of features that fall in the image regions that are photometrically far from the adaptation level of the observer. The calibration is done by showing the observer a set of 8 small square patches against a background of gaussian noise that has about the same variance as a mammogram. The mean luminance is varied over 8 levels from black to white and the just noticeable difference (JND) is recorded. A curve of JND as a function of luminance is drawn. The curve is characterized by a polynomial which is used to modify the basic system look-up table (LUT).

6.2.3 Image/Display coupling optimization

The final step in presenting the display is identifying the clinically significant regions of the image to maximize the number of intensities available for target discrimination. These regions will be determined from the analysis of eye position data of experts viewing mammograms.

6.3 Develop a computer controlled roving window based upon eye position distribution patterns over mammograms.

The distribution of eye fixations over images will be recorded in a number of expert mammographers. The summed distributions will be correlated with image features such as average intensity (density) , dominant edges and curved edges. This information will be used to develop search strategies for new images. The strategies will be implemented by a roving window on the display.

6.4 Results

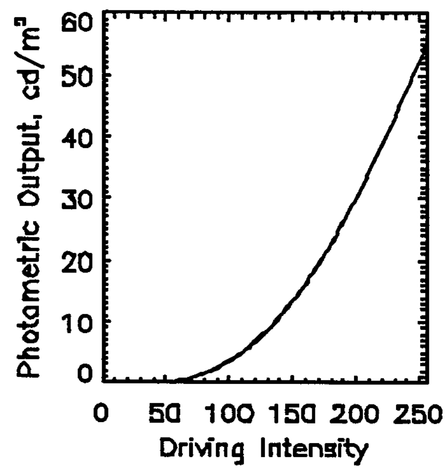
6.4.1 Lesion simulator

The lesion simulator has been developed and successfully used in preliminary tests of visual contrast sensitivity.

6.4.2 Photometric calibration

The photometric calibration is shown in Figure 6.4.1

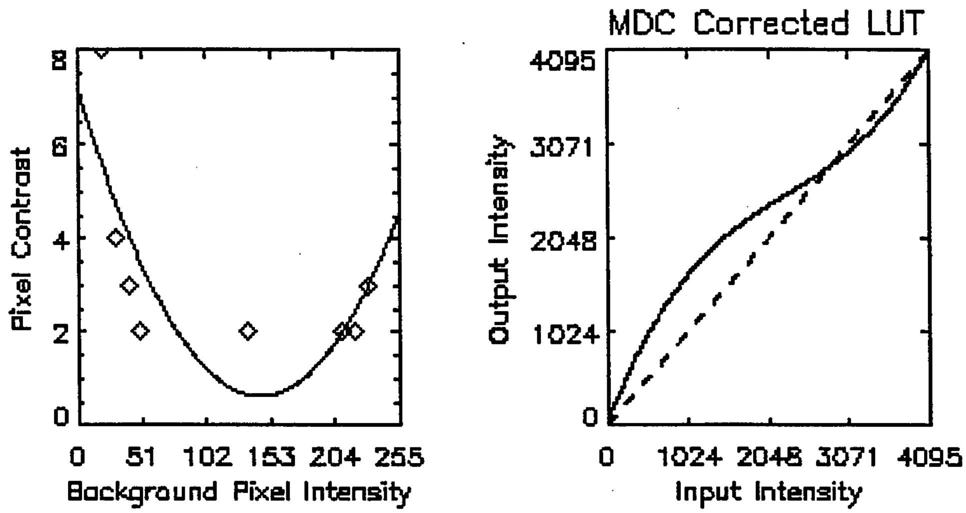
Figure 6.4.1 Display Function Resulting from Photometric Calibration



6.4.3 Perceptual calibration under ambient lighting conditions.

Using the photometrically calibrated display , circular 1 cm. targets with a range of contrasts are displayed in known locations to the observer, who chooses the targets that are just visible. The adaptive level of the observers eyes depends on both the existing room lighting and the overall brightness of the display. Ambient light affects contrast sensitivity by influencing the light adaptation level of the eye, by scattering off the display surface and by scattering within the eye. This reduces the perceived contrast of image features. The resulting database determines the minimum contrast (pixel driving level) required to detect the target at each of eight background intensities. (see Figure 6.4.2a) These data are fit by a second degree polynomial equation, which becomes a basis function for the minimal detectable contrast (MDC) calibration. The relationship is modeled by a parabolic function. This function is normalized to provide sufficient correction to render test pattern targets approximately equally detectable at a given (pixel driving level) contrast. The curve is integrated to derive the MDC corrected LUT shown in Figure 6.4.2b.

Figure 6.4.2 a) On the left are the calibration data points and the curve fitting parabola.
b) On the right is the look up table (LUT) that results by integrating the best fit parabola.



7. Conclusions

The CRT can be simply calibrated to correct for ambient illumination. Although the calibration works with test patterns it still has to be tested using real mammograms.

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Optimizing the visualization of projection images using a photometric, psychometric, and image based calibration procedure.

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ABSTRACT

We propose a method for improving the visualization of potential target regions in radiographic projection images. This is accomplished by modifying the intensity lookup tables (LUT) to compensate for, 1) cathode ray tube (CRT) dynamic range limitations and, 2) for contrast sensitivity characteristics of the human eye. We match the resulting LUT to selected regions of the image to optimize the use of the available intensity range.

Keywords: contrast sensitivity, psychometric calibration, LUT optimization

1. INTRODUCTION

Display technologies have evolved over recent years to yield improved resolution and dynamic display intensity range, but they still fall short of achieving the resolution and dynamic range visible on standard x-ray film. CRT technologies are producing displays that can render images with a dynamic range of about 2.0-2.5 orders of magnitude (100:1 to 300:1) whereas, film is capable of 3.0-3.5 orders of magnitude (1000:1 to 3000:1). To partially compensate for the limited range of CRT displays, observers are required to vary the window width and window level. Details that fall outside of the windowed intensities are usually clipped and detailed features can be lost.

Subjective impressions of observers often favor high contrast representations[1] as the best rendering of an image, even though details are lost due to intensity clipping. These images may appear more aesthetically pleasing, but may contain less useful information.

Without knowledge of the location of potential lesion sites, the window width and level that will render a subtle lesion visible might only be found by laborious trial and error. Moving the window level and width to visualize different regions of an image is a common cure for dynamic range limitations of CRT displays.

It has been shown that the contrast sensitivity of the human eye is related to the adaption level of the observer and the focal luminance surrounding the point of gaze[2]. Therefore, it may be advantageous to initially display an image with an intensity lookup table (LUT) that adjusts the image appearance to compensate for the factors limiting the contrast sensitivity of the human observer[3,4,5]. In the contrast sensitivity curves shown in figure 1, the dashed curves illustrate the decrease in sensitivity of the observer to low contrast targets as the local luminance deviates from the observer's light adaption level. Observers demonstrate maximum sensitivity to low contrast targets when the local luminance is close to their adaptation level.

Using this knowledge, we create a LUT that compensates for decreased contrast sensitivity by selectively increasing the contrast at the low and high luminance levels in the image. The resulting nonlinear correction to the LUT results in what we refer to as a "tempered" display.

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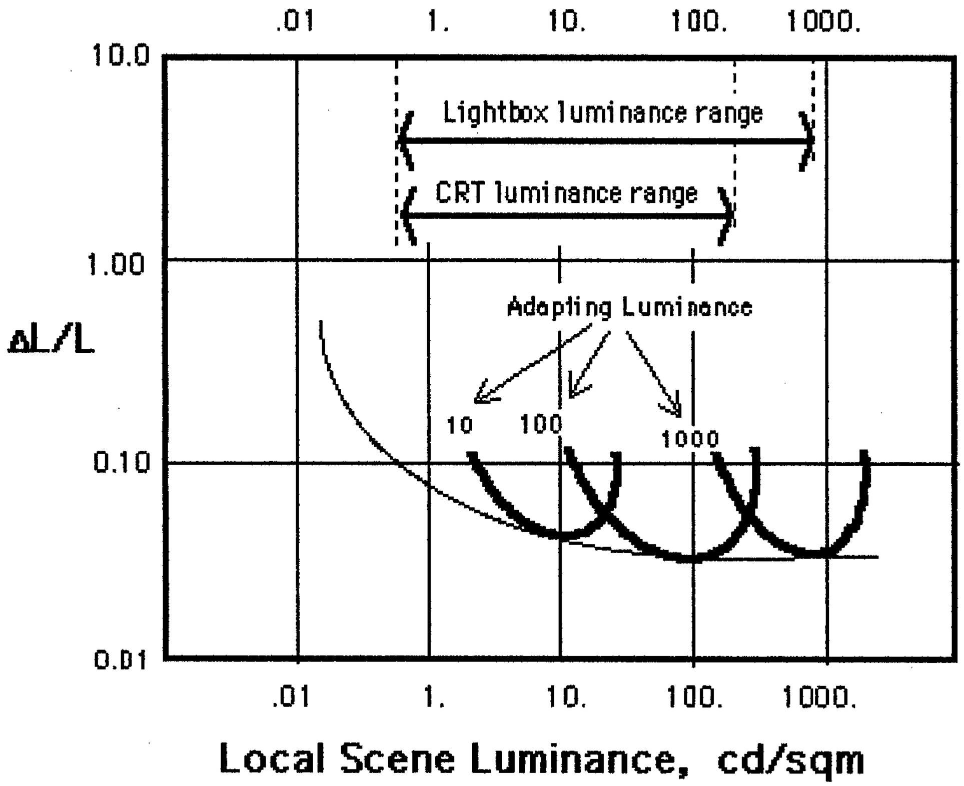


Figure 1.

2. METHODS

The following methods were developed on a Sun Sparc10 workstation(Sun Microsystems Computer Corporation, Mountain VIew, CA). All software was written in Interactive Data Language (Research Systems, Inc., Boulder, CO), a high level graphics language with the capability of being run on a variety of computer platforms and operating systems. Though the display buffer is capable of displaying only 8-bit image data, all processing of image data and LUTs occurred with 12-bits of resolution (4096 gray levels). Only after all mathematical operations are performed are the final 8-bit images produced. This was necessary to retain image pixel intensity resolution throughout the image manipulation process.

A - Photometric Calibration

So that the display characteristics were standardized from one session to the next, we photometrically calibrated the CRT using a Tektronix J17 Photometer with a J1803 luminance probe (Tektronix Inc., Beaverton, OR). This is a semi-automated procedure that is software controlled. The photometer probe was attached to the face of the display with a suction cup. A central square region on the display measuring 10 centimeters on a side was stepped through 17 intensity levels that ranged from black to white. These data were used to generate a polynomial equation that equated the driving level with the photometric output of the CRT (figure 2). The photometric calibration process quantified the monitor characteristics. This facilitated setting the monitor to a similar state in subsequent sessions.

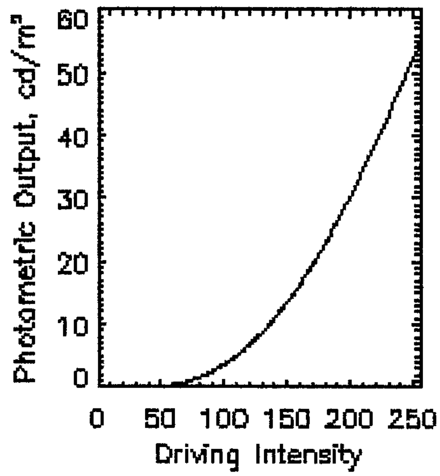


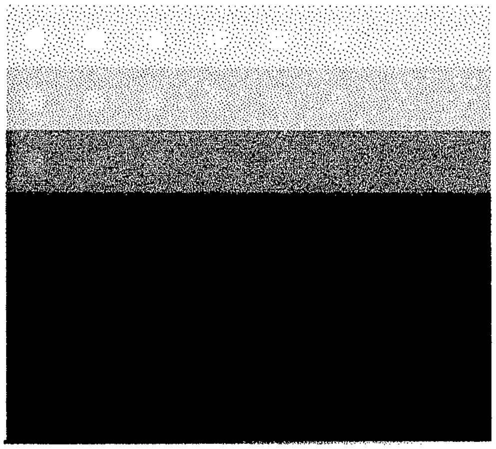
Figure 2.

B - Psychometrics

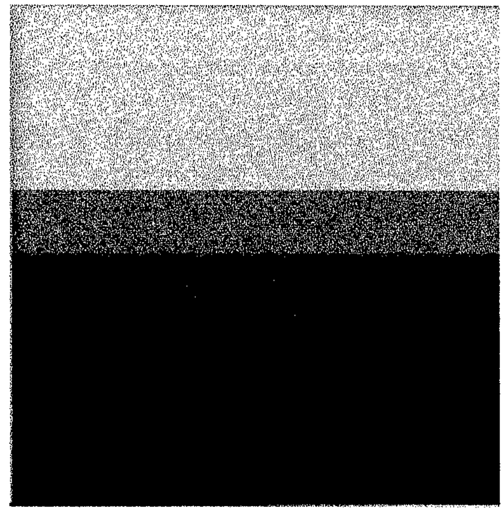
The calibration process is simple and can be accomplished quickly. We calibrated the observer's contrast sensitivity using a "minimum detectable contrast" (MDC) calibration procedure over a wide range of available intensities. Circular 1 cm. targets with a range of contrasts are displayed in known locations to the observer, who chooses the targets that are just visible (figure 3A). The adaptive level of the observers eyes depends on both the existing room lighting and the overall brightness of the display. Ambient light affects contrast sensitivity in two ways. Firstly, by influencing the light adaption level of the eye, and secondly, by scattering off the display surface and reducing the apparent contrast of image features.

The resulting database relates the minimum contrast (pixel driving level) required to detect the target at each of eight background intensities. These data are fit by a second degree polynomial equation, which becomes a basis function for the MDC calibration. For our test monitor, the relationship is modeled well by a parabolic function. This function is normalized to provide sufficient correction to render test pattern targets approximately equally detectable at a given (pixel driving level) contrast. We integrate this curve to derive the MDC corrected LUT (figure 4).

These psychophysical measures show that at any light adaptation level of the human eye, performance degrades when the target surround is sufficiently different from the light adaptation level of the eye. The psychophysically derived correction was applied to the display lookup tables to increase the displayed contrast of features that fell in the image regions that are photometrically far from the adaptation level of the observer (figure 3B). Since there is a limited dynamic luminance range in the CRT display, the gain in contrast in one segment of the luminance range will be borrowed from another segment. Thus, the resulting tempered display constitutes a compromise in the assignment of luminance levels to image pixel values. Although the contrast is enhanced in the darker and lighter regions of the image, contrast is reduced in those intensity range(s) where the observer proves most sensitive.

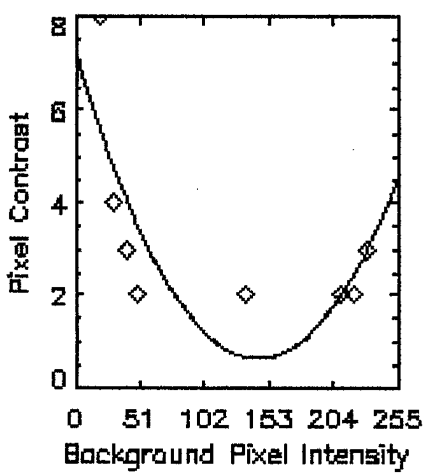


A - Target Test Pattern



B - Target Test Pattern after application of the MDC Corrected LUT

Figure 3.



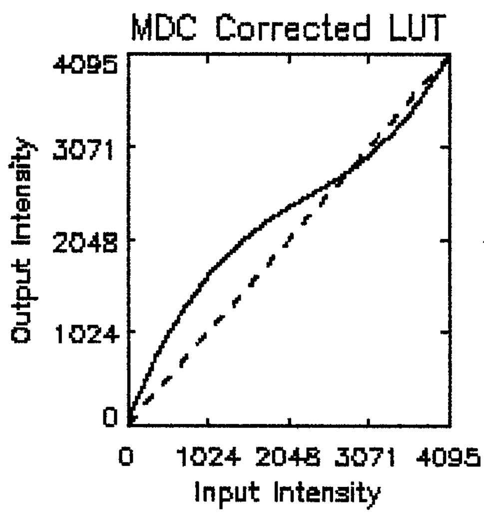
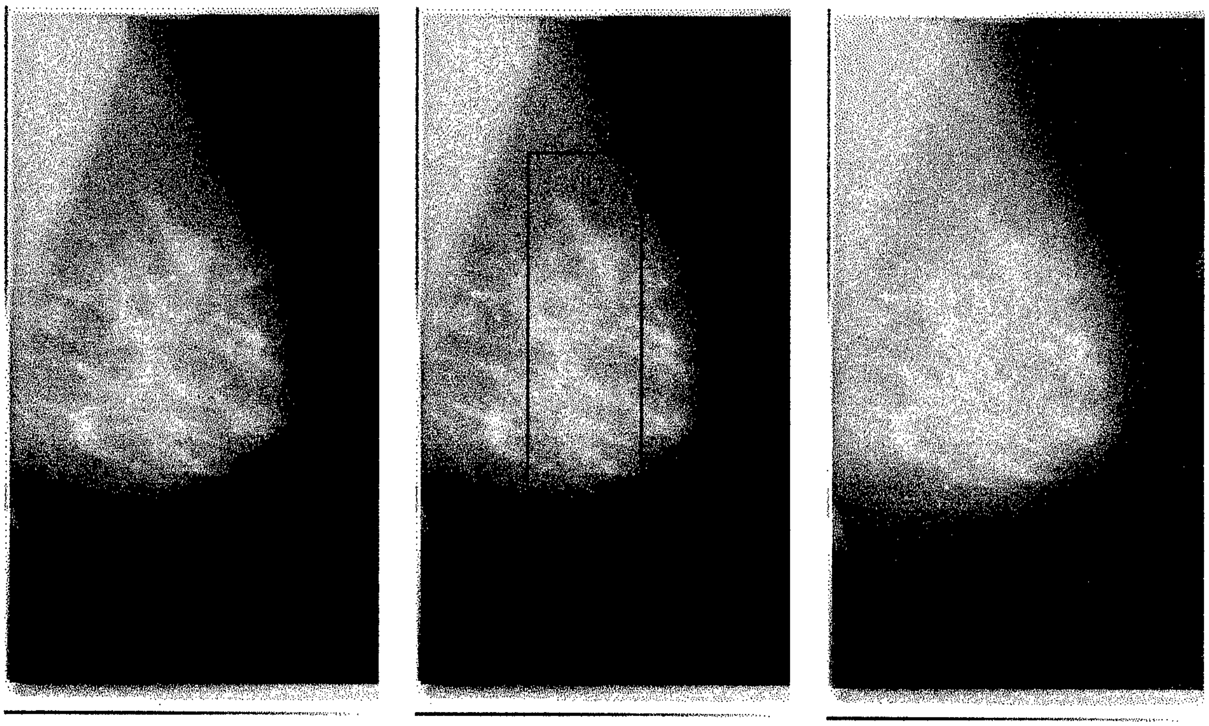


Figure 4.

C - MATCHING LUT TO IMAGE

The resulting MDC corrected LUT is matched to selected regions of the image to maximize the number of intensities available for target discrimination. The regions are selected by the user who uses the cursor to define a rectangular region of any size containing the anatomical tissue of interest. Extremely underexposed (behind lead labels) and overexposed (no anatomical tissue) regions of the image should not be included in the optimization segment. We hope to include automated segmentation in the future.

The breast image in figure 5 illustrates the effect of applying the MDC compensated LUT to the range of intensities within the segmented portion of the image. The skin line becomes apparent (figure 5C), though the overall contrast of the image is somewhat reduced.



A - Original Breast Image

B - Original Breast Image with Selected Segment for Optimizing Grayscale

C - MDC Corrected LUT applied to Selected Segment

Figure 5.

In this initial evaluation phase of the project, the software has been written to allow the observer to apply the MDC corrected LUT, return to the linear function with normal window level and width, or utilize specially designed nonlinear LUTs that are based on adjustable general purpose gaussian or parabolic basis functions.

3. CONCLUSIONS

The minimum detectable contrast of observers varies with light adaptation levels and with display charateristics. We have created an intensity adjusted image display using psychometrically derived intensity lookup tables to increase overall target visibility in test patterns. The MDC calibration process is quick and simple to perform. Subjective evaluations confirm that following this display optimizing results in improved visualization of targets in the test pattern images. We propose this method for improving the visualization of potential target regions in radiographic projection images. Observer performance studies will test this hypothesis.

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